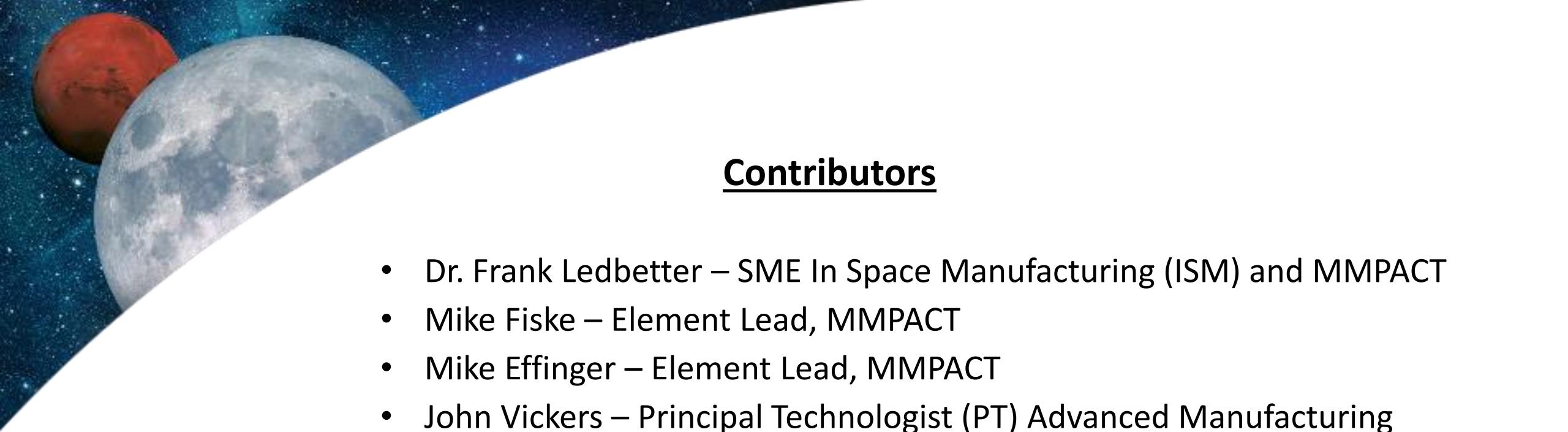




Out of Earth Manufacturing: NASA's Efforts to Address Exploration Logistics Challenges through In Space Manufacturing and Extraterrestrial Construction

1st International Conference on Additive Manufacturing for Air, Space, and Land Transportation

R. G. Clinton, Jr., PhD; March 7-11, 2022



Contributors

- Dr. Frank Ledbetter – SME In Space Manufacturing (ISM) and MMPACT
- Mike Fiske – Element Lead, MMPACT
- Mike Effinger – Element Lead, MMPACT
- John Vickers – Principal Technologist (PT) Advanced Manufacturing
- Dr. Mark Hilburger – PT Excavation, Construction, and Outfitting
- Dr. Tracie Prater – Foundational Surface Habitat
- Jason Ballard – CEO ICON Technologies
- Evan Jensen – ICON PM MMPACT



Agenda

- Artemis: Phases 1 and 2
- Space Technology Mission Directorate: Technology Drives Exploration
 - Lunar Surface Innovation Initiative (LSII)
 - Why Out of Earth Manufacturing and Construction
 - Excavation, Construction, and Outfitting (ECO)
 - Challenges and Capability Gaps
 - Advanced Manufacturing
 - In Space Manufacturing (ISM) – Portfolio and Challenges
- Questions

Artemis: Landing Humans On the Moon

Lunar Reconnaissance
Orbiter: Continued
surface and landing
site investigation

Artemis I: First
human spacecraft
to the Moon in the
21st century

Artemis II: First humans
to orbit the Moon and
rendezvous in deep space
in the 21st Century

Gateway begins science operations
with launch of Power and Propulsion
Element and Habitation and
Logistics Outpost

Artemis III-V: Deep space crew missions;
cislunar buildup and initial crew
demonstration landing with Human
Landing System

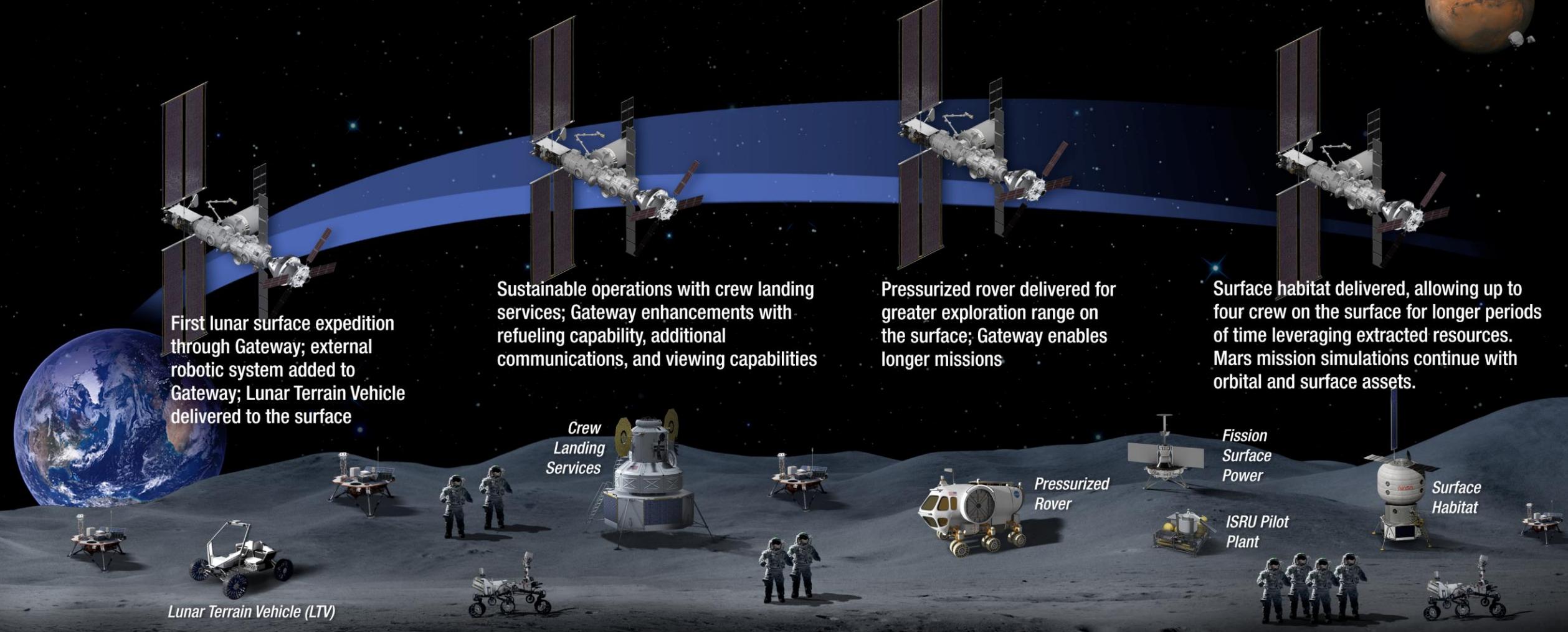
Early South Pole Robotic Landings
*Science and technology payloads delivered by
Commercial Lunar Payload Services providers*

Volatiles Investigating Polar Exploration Rover
First mobility-enhanced lunar volatiles survey

Humans on the Moon - 21st Century
First crew expedition to the lunar surface

LUNAR SOUTH POLE TARGET SITE

Artemis Base Camp Buildup



SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

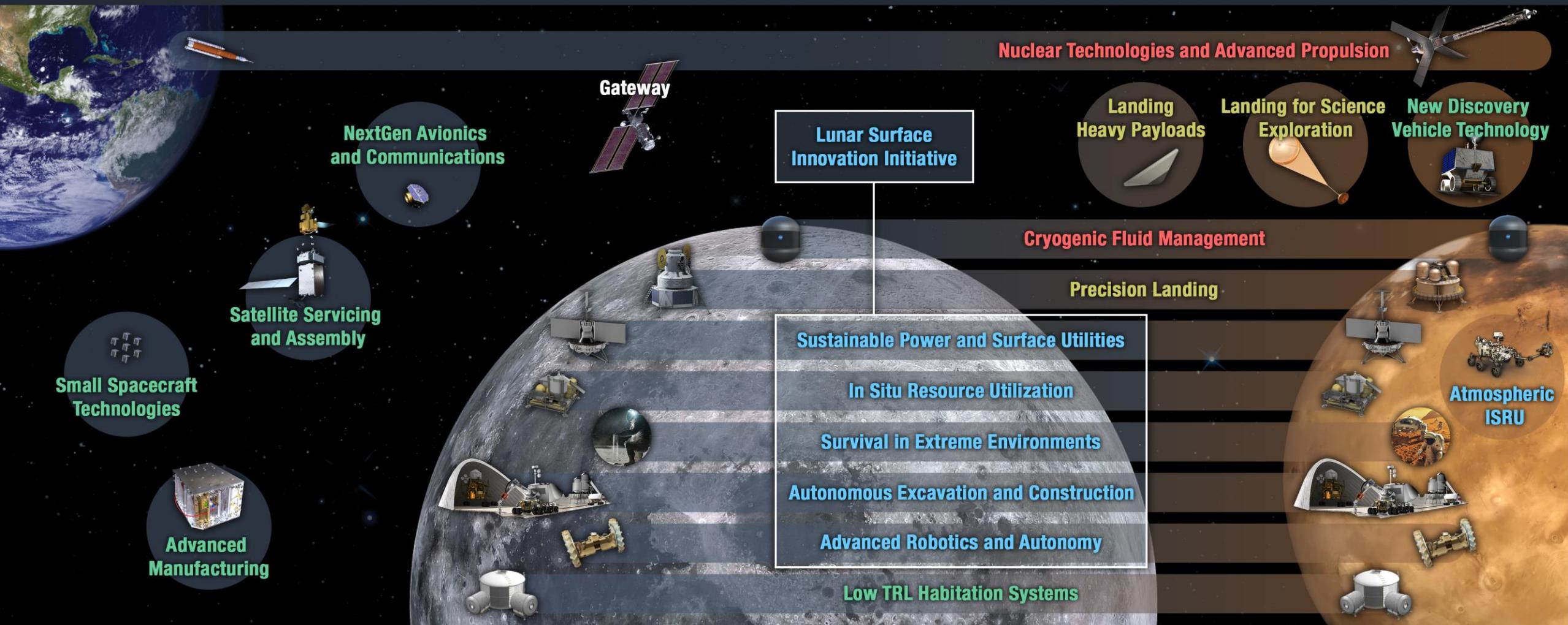
TECHNOLOGY DRIVES EXPLORATION

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries

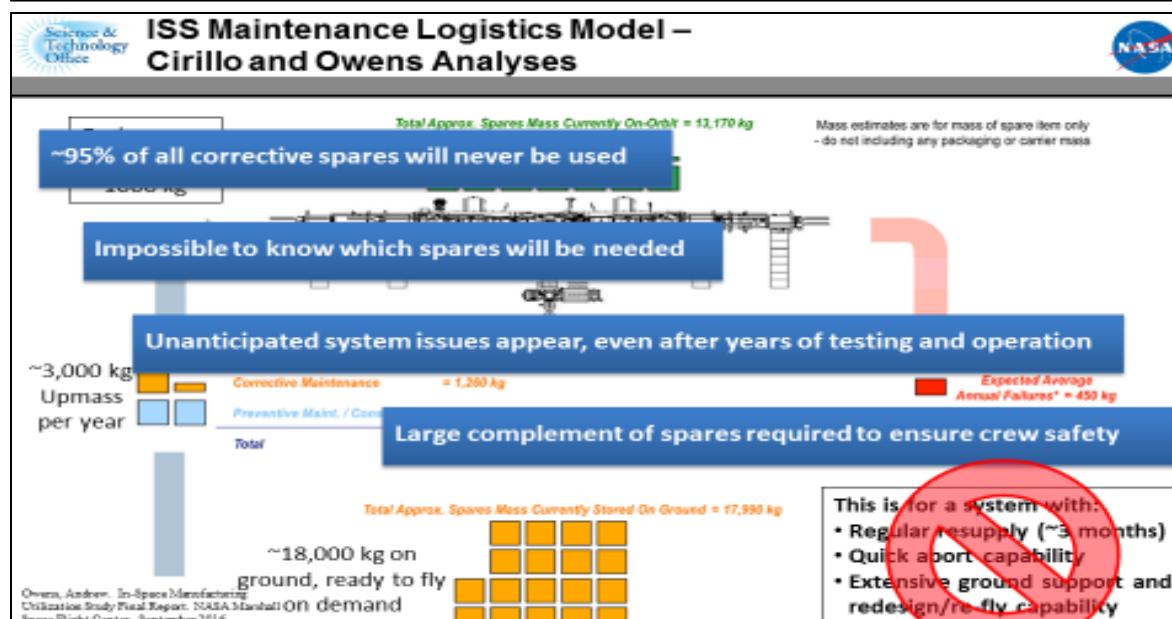
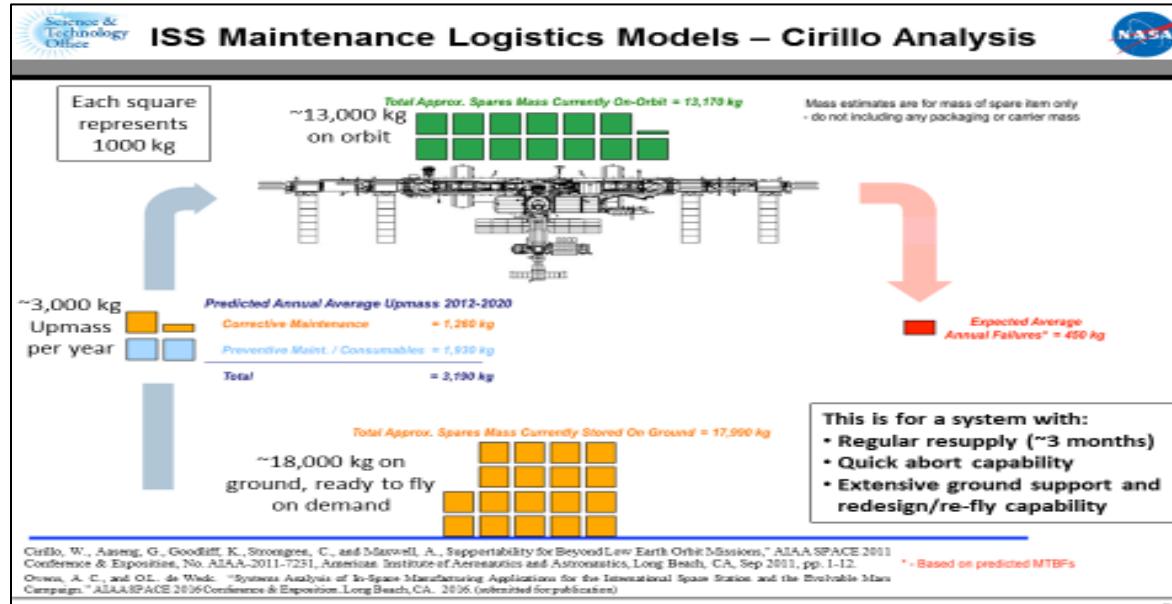


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The Case for In Space Manufacturing: WHY



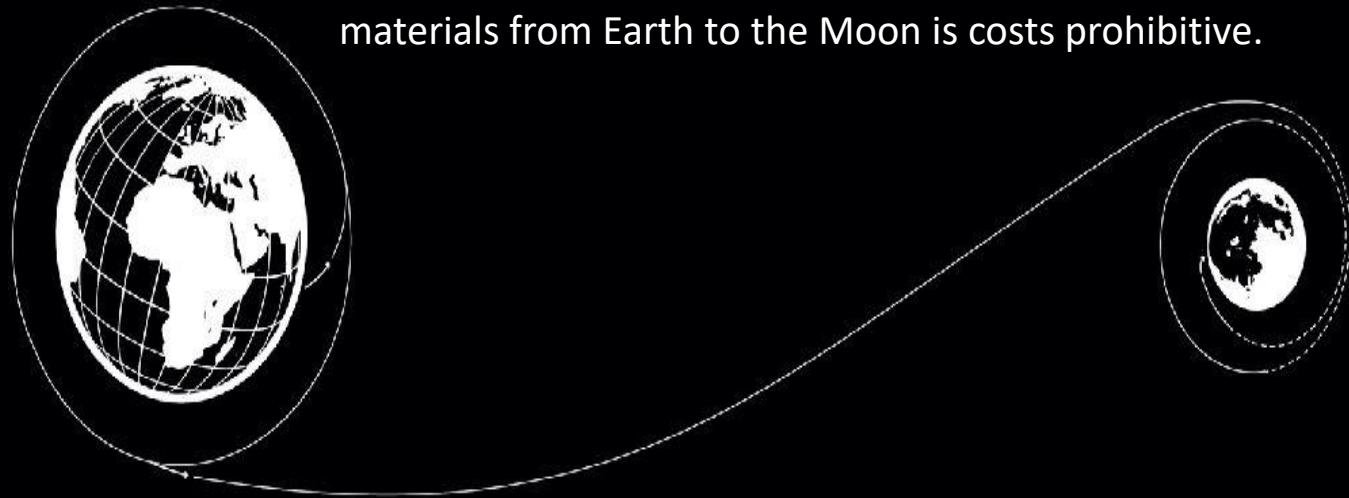
Current maintenance logistics strategy will not be effective for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

Rockets are not efficient movers of building materials. Even with commercial space flight dramatically dropping the launch costs to all-time historic lows, flying pre-built structures doesn't make financial sense. Even flying building materials from Earth to the Moon is costs prohibitive.



\$ 0.29 x Kg

Cost of Portland Cement on earth

\$ 0.11 per Kg

Costs of dry ICON Lavacrete on Earth

\$ 10,000 per home

Dry concrete costs to print
an avg. 1200 sq ft home.

\$ 3,210.29 x Kg

Cost of Portland Cement on lunar surface*

\$ 15,000 per Kg

Cost per Kg of Lavacete to Lunar Surface

\$ 1,400,000 per home

Dry concrete costs to print a

350 sq. ft. structure like the
Chicon House on the Moon.

COST OF 1KG OF CEMENT

*Calculated from current price per kg for SpaceX access to the ISS (\$2,720)
and cost of dry concrete to print a 350 sq. ft. structure like the Chicon House on the Moon (\$307 x kg)

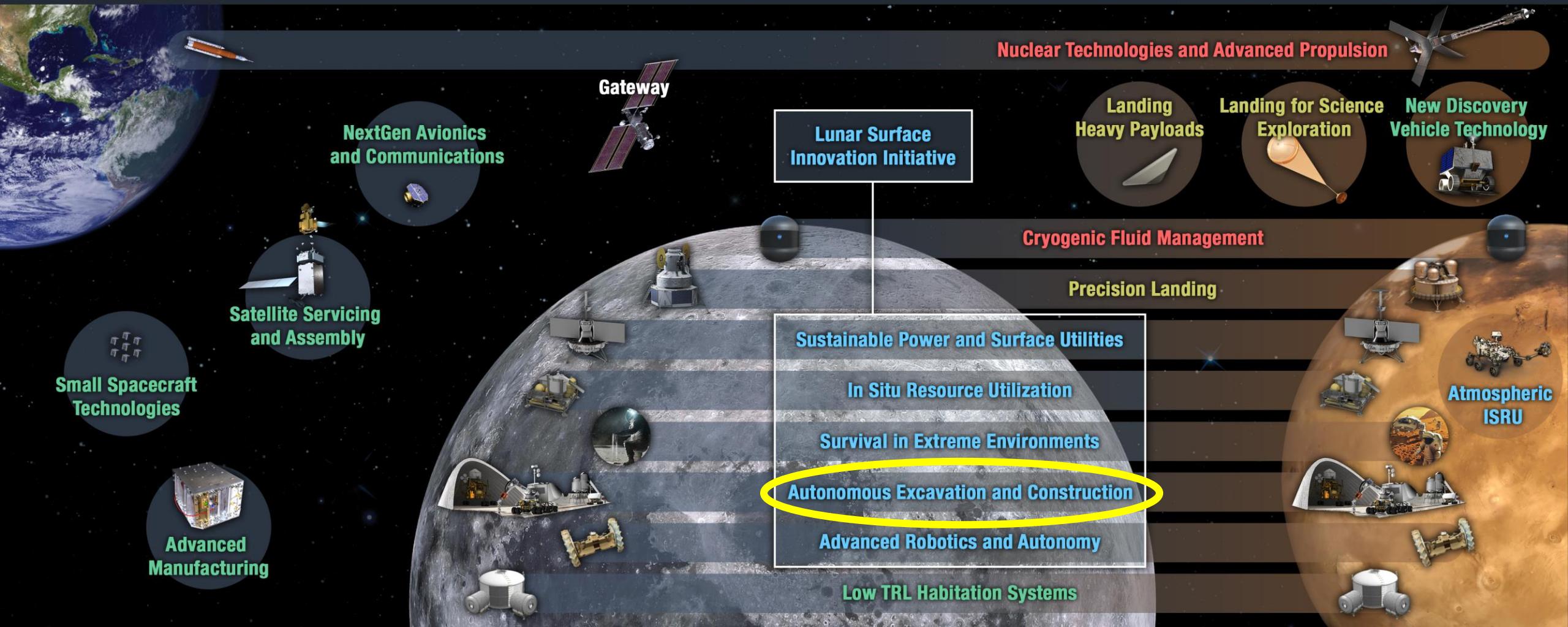
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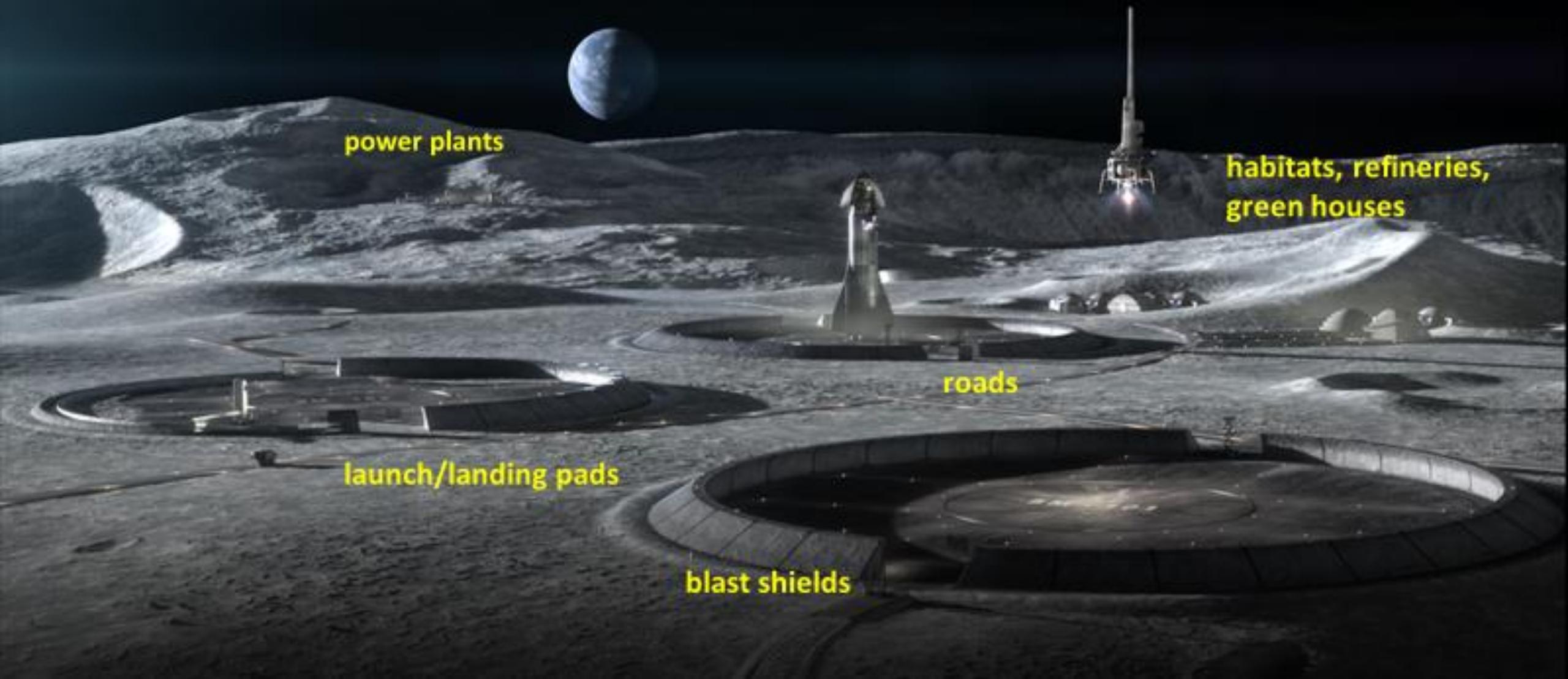
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Building a Sustainable Presence on the Moon

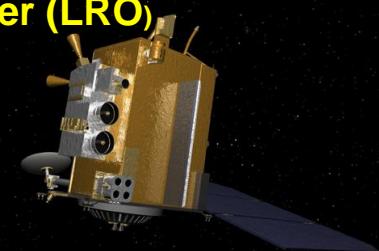
- What infrastructure are we going to need?



Excavation for ISRU and Construction: *Finding, Excavating and Transporting the Resources*

Resource Prospecting –
Looking for Resources

Lunar Reconnaissance
Orbiter (LRO)



Volatiles Investigating Polar
Exploration Rover (VIPER)
~2024 mission

Excavation & Processing
for Aggregates and Binders



RASSOR
Excavator
~2026 mission



Moon-to Mars Planetary Autonomous Construction Technologies (MMPACT) Overview

GOAL

Develop, deliver, and demonstrate on-demand capabilities to protect astronauts and create infrastructure on the lunar surface via construction of landing pads, habitats, shelters, roadways, and blast shields using lunar regolith-based materials.



MMPACT is structured into three interrelated elements:

1. Olympus Construction Hardware Development
2. Construction Feedstock Materials Development
3. Microwave Structure Construction Capability (MSCC)

OBJECTIVES

- Develop and demonstrate additive construction capabilities for various structures as materials evolve from Earth-based to exclusively *In Situ* Resource Utilization (ISRU)-based.
 - Develop cementitious blends that can originate from *in situ* resources for Olympus.
 - Develop directed energy – based construction technologies
 - Develop molten regolith construction concepts
- Develop and demonstrate approaches for integrated sensors and process monitoring in support of *in situ* verification & validation of construction system and printed structures.
- Test and evaluate Olympus and MSCC products for use in the lunar environment.
- Validate that Earth-based development and testing are sufficient analogs for lunar operations

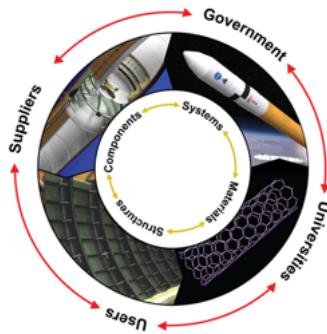
MMPACT – Current Partners

NASA Centers

- MSFC
- LaRC
- KSC
- JPL

OGA Leveraging

- Potential:
- Innovation Unit US Air Force (AF)
- Contributing:
- AF Civil Engineering Center
 - AF Special Operations Command
 - Defense Innovation Unit
 - Texas Air National Guard
 - USAF



Public/Private Partnerships

- Dr. Holly Shulman
- ICON Build
- Radiance Technologies
- RW Bruce Associates, LLC
- Blue Origin
- Jacobs Space Exploration Group
- JP Gerling
- Logical Innovations
- Microwave Properties North
- MTS Systems Corp.
- Southeastern Universities Research Association
- Southern Research
- Space Exploration Architecture (SEArch+)
- Space Resources Extraction Technologies
- Sioux Tribes
- Astroport

Technology Providers/ Contributing Partners: Academia

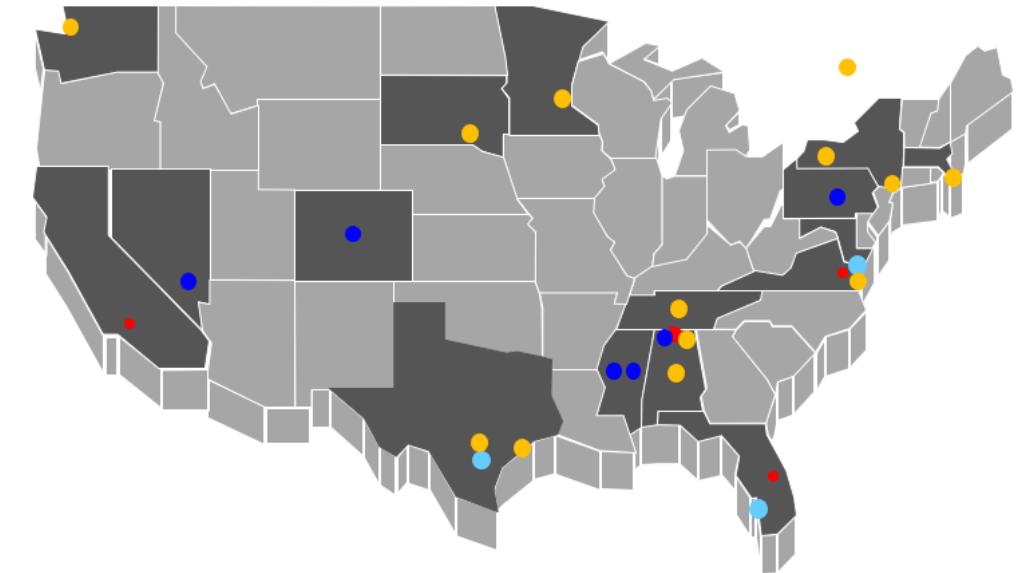
- Colorado School of Mines
- Drake State
- Mississippi State University
- Pennsylvania State University
- University of Mississippi
- University of Nevada Las Vegas

SBIR/STTR

- Construction Scale Additive Manufacturing Solution

Potential Customer

- Artemis



Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

Autonomous Construction for the Lunar Outpost

Regolith-based Materials and Processes:

- Cementitious
- Geopolymers/Polymer
- Thermosetting materials
- Regolith Melting/Forming
- Laser sintered
- Microwave sintered

Image courtesy of ICON



Image courtesy of Bjarke Ingels Group

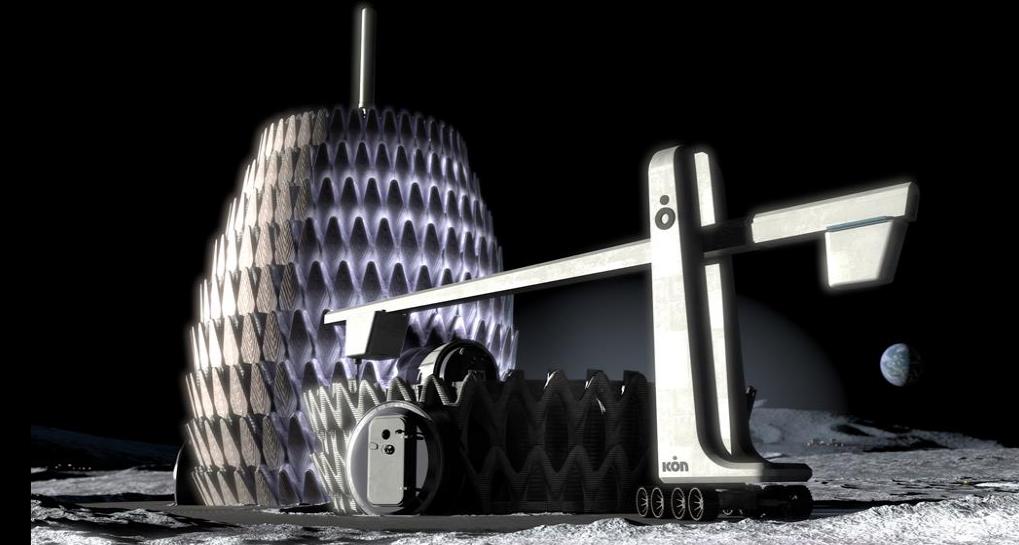
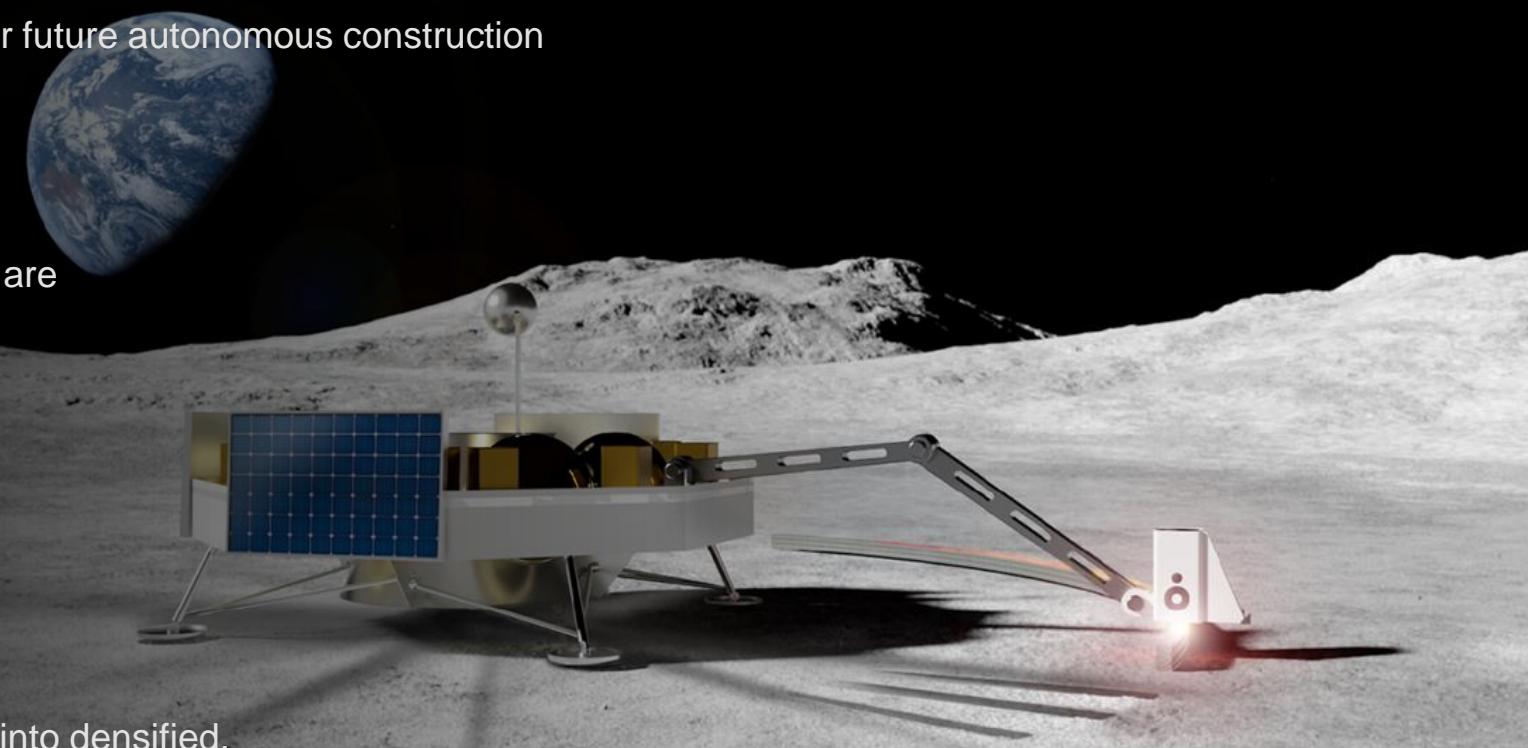


Image courtesy of Search+

Initial Construction Technology Demonstration Mission, DM-1 (2026)

Construction Roadmap

- Demonstrate downselected construction technique utilizing ISRU materials at small scale from lander base (horizontal and vertical subscale “proof of concept” elements)
- Results are critical to inform future construction demonstrations & characterize ISRU-based materials and construction processes for future autonomous construction of functional infrastructure elements
- Demonstration of remote/autonomous operations
- Initial demonstration of instrumentation and material
- Validation that Earth-based development and testing are sufficient analogs for lunar operations
- Anchors analytical models
- **Rationale:** Must prove out initial construction concept in lunar environment



Outcome

- TRL 6 achieved for autonomous ISRU consolidation into densified, subscale horizontal and vertical demonstration products
- TRL 9 for limited hardware and instrumentation that will be used on later missions

Lunar Construction Capability Development Roadmap

Phase 1:
Develop & demonstrate excavation & construction capabilities for on-demand fabrication of critical lunar infrastructure such as landing pads, structures, habitats, roadways, blast walls, etc.

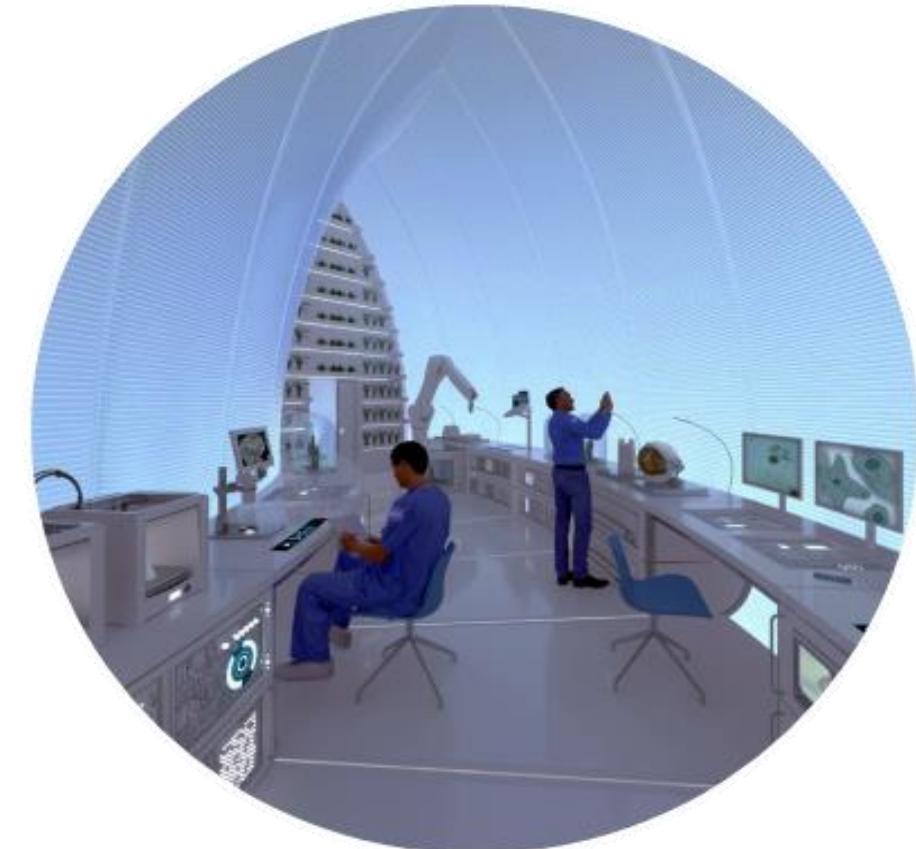
Phase 2: Establish lunar infrastructure construction capability with the initial base habitat design structures.

Phase 4: Complete build-out of the lunar base per the master plan and add additional structures as strategic expansion needs change over time.

Phase 3: Build the lunar base according to master plan to support the planned population size of the first permanent settlement (lunar outpost).

Lunar Outfitting Capability Development

- Outfitting: Broad spectrum of capabilities – “Turning a house into a home”
- In-situ installation of subsystems
 - Mechanical
 - Electrical
 - Plumbing (ducting, piping, gas storage)
- Interior Furnishings Fabrication
 - Workbenches
 - Tables
 - Chairs
- Power, Lighting, Communications
- Enclosures (windows, hatches, bulkheads)
- Verification, Validation, and Inspection Technologies



Challenges and Capability Gaps

- Reduced gravity and low reaction forces – Excavation
- Inspection and Certification of as-built structure – Construction
- Material and construction requirements and standards - Construction
- Process Development and Demonstration
 - ISRU for extraction of basic products:
 - Consumables – water, oxygen, and volatiles capture
 - Feedstock materials – metals, alloys and binder constituents
 - Construction: Deposition processes and associated materials
- Scale Up
 - ISRU production (10's to 100's mT)
 - Excavation: (10's to 1000s mT); Trips/Distance traversed
 - Construction: Proof of concept to full scale landing pads and habitats
- Regolith excavation, transfer, and conveyance
- Long-duration operation of mechanisms and parts under lunar environmental conditions (Reliability and Maintainability)
- Structural Health Monitoring and Repair
- Dust Mitigation
- Increased Autonomy of Operations
- Power

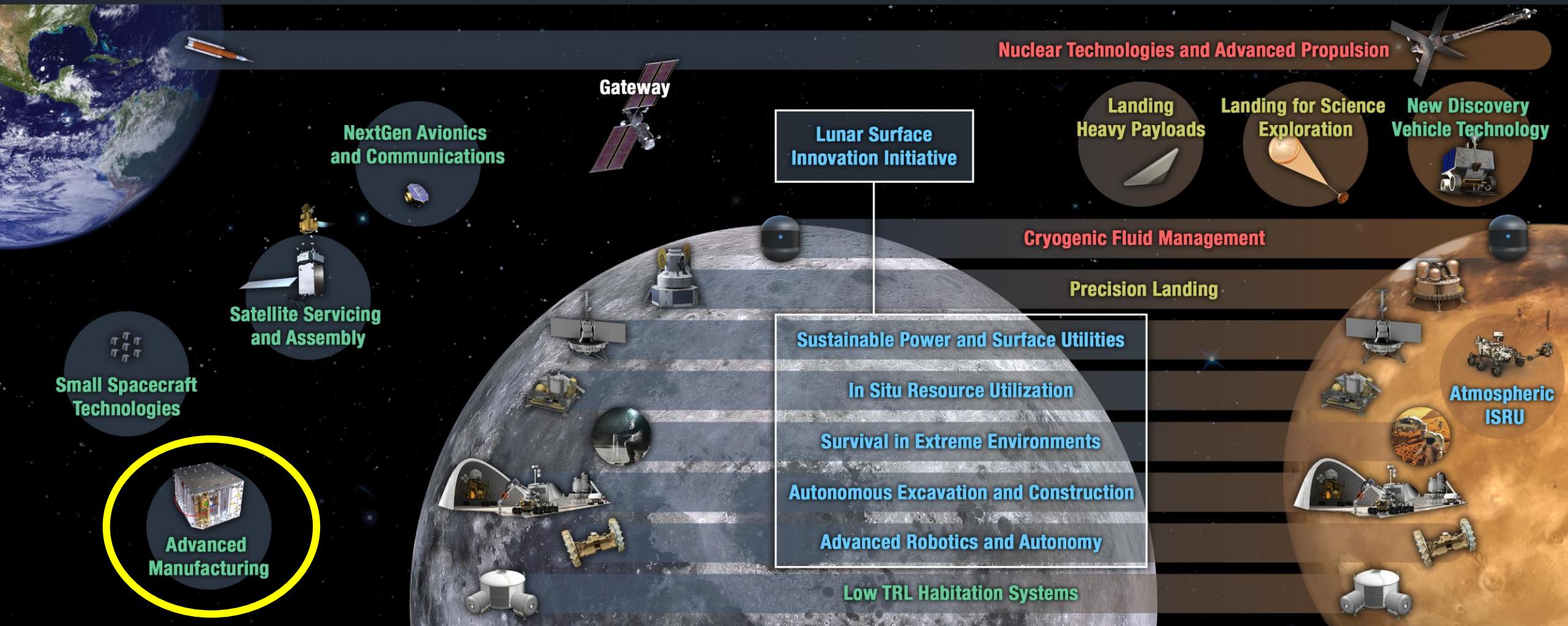
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In-Space Manufacturing Project Portfolio

Objective: provide a solution towards sustainable, flexible missions through development of on-demand fabrication, replacement, and recycling capabilities

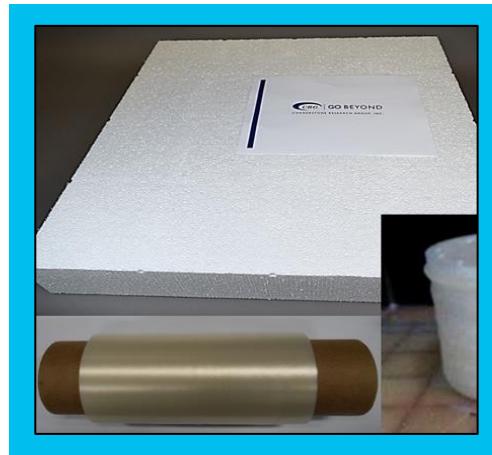
On Demand Metals Manufacturing



Provide a capability for on-demand 3D printing of metal parts

Image Courtesy of Made In Space

Recycling and Reuse



Develop materials and recycling technologies to create an on-orbit recycling ecosystem

Image Courtesy of Cornerstone Research Group

On Demand Electronics Manufacturing



Develop printed electronics, sensors, and power devices for testing and demonstration on ISS

Development and Testing of Capabilities for On-Demand Spare Component Manufacturing



Techshot Fabrication Laboratory ground-based prototype for bound metal deposition. Image from Techshot, Inc.



Vulcan wire+arc hybrid additive manufacturing system from Made in Space, Inc.

Systems in development for future initial ISS demonstrations: 3D printing of metals

Adapting Metal AM for ISS and Lunar Surface Environments

Environments (ISS and the lunar surface) impose unique constraints for manufacturing systems.

- Scale/scalability of hardware
 - Power (max power for ISS payload is 2kW)
 - Mass
 - Volume
- Safety (feedstock management, chip debris capture)
- Limited crew interaction
- Remote commanding
- Range of materials within processing capability
- Feedstock materials available, via beneficiation, on Moon
- Ability to produce complex features
- Surface finish
- Operation in reduced gravity
 - Physics of deposition
 - Impact on material quality
 - Management of heat in absence of natural convective cooling

One of the pre-eminent ISM challenges is verification of parts produced on-orbit or on the lunar surface.

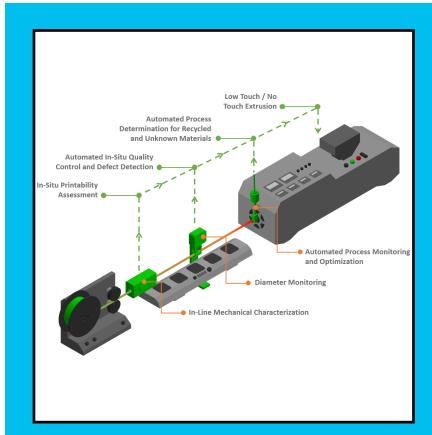
Recycling and Reuse (RnR)

The RnR project element develops materials and recycling technologies with the goal of creating an on-orbit ecosystem for repurposing waste products, such as packaging materials and defective components.



Cargo bags filled with trash on ISS for downmass in Cygnus cargo capsule. Image from NASA.

- Analyze historical waste streams and recycling technologies
- Development of “purpose-built” recyclable materials
- Development of in process monitoring technologies



(LEFT) Thermally reversible packaging materials (which can also be used for 3D printing) and (RIGHT) in-process monitoring system for polymer filament production from Cornerstone Research Group (CRG). Images from CRG.

Potential Areas for Future Exploration

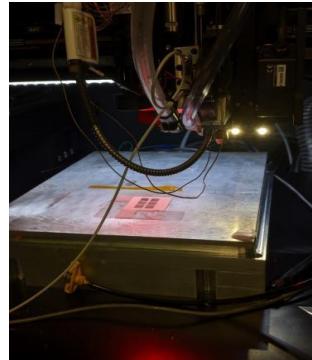
- Metals Recycling
- Sterilization and Sanitization Technologies
- Increased feedstock strength
- Validation and characterization of recycled feedstock
- In Situ Resource Extraction
- Cleaning Technologies (esp. food packaging)
- Disassembly of multi material products

On-Demand Manufacturing of Electronics (ODME)

ODME is developing printed electronics, sensors, and power devices for initial testing and demonstration on ISS. In parallel, deposition processes used with printed electronics (direct write and plasma spray) are being matured for future flight demos.



Development of electronic inks



Development of laser sintering process



Development of photonic sintering process



Dimatix inkjet thin film printer



nScript 3D Multi-Material Printer



*Printed cortisol (stress) sensor.
Image from California Institute of Technology.*



Diagram of AstroSense next-generation flexible, wireless, multi-sensor printed device for crew health monitoring. Image from Nextflex.

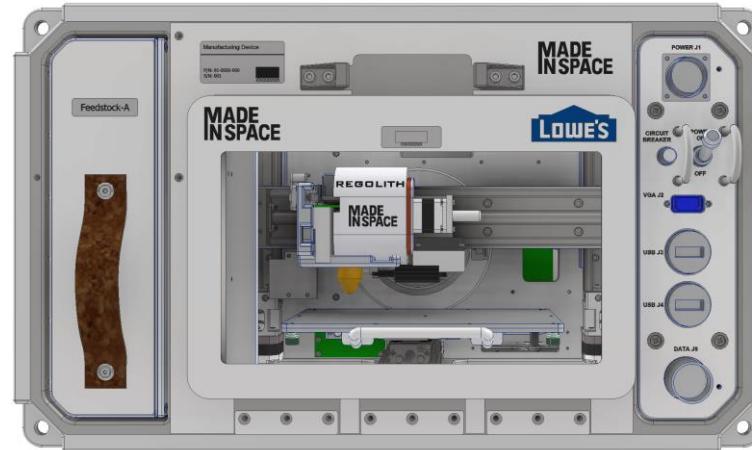


1st Generation Personal CO₂ Monitor



3D Printing and In Situ Resource Utilization (ISRU): RegISS demonstration

RegISS will be an on-orbit demonstration of 3D printing with a polymer/regolith simulant feedstock blend. It will be the first demonstration of manufacturing with ISRU-derived feedstocks on ISS.



Made in Space (MIS) owns and operates the Additive Manufacturing Facility (AMF).

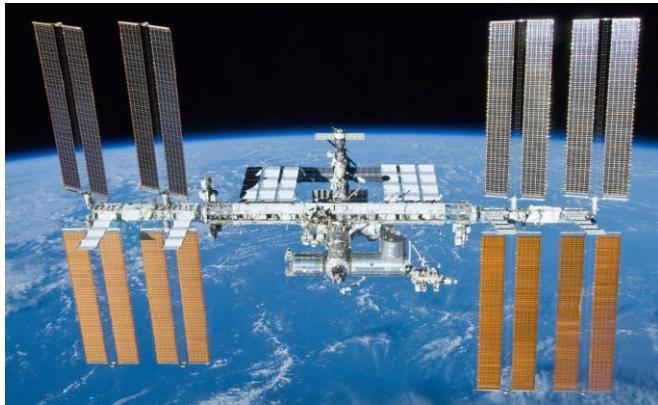
In this effort, a previously flown version of AMF will be modified to accommodate a new extruder and print with a feedstock consisting of regolith simulant and a thermoplastic.



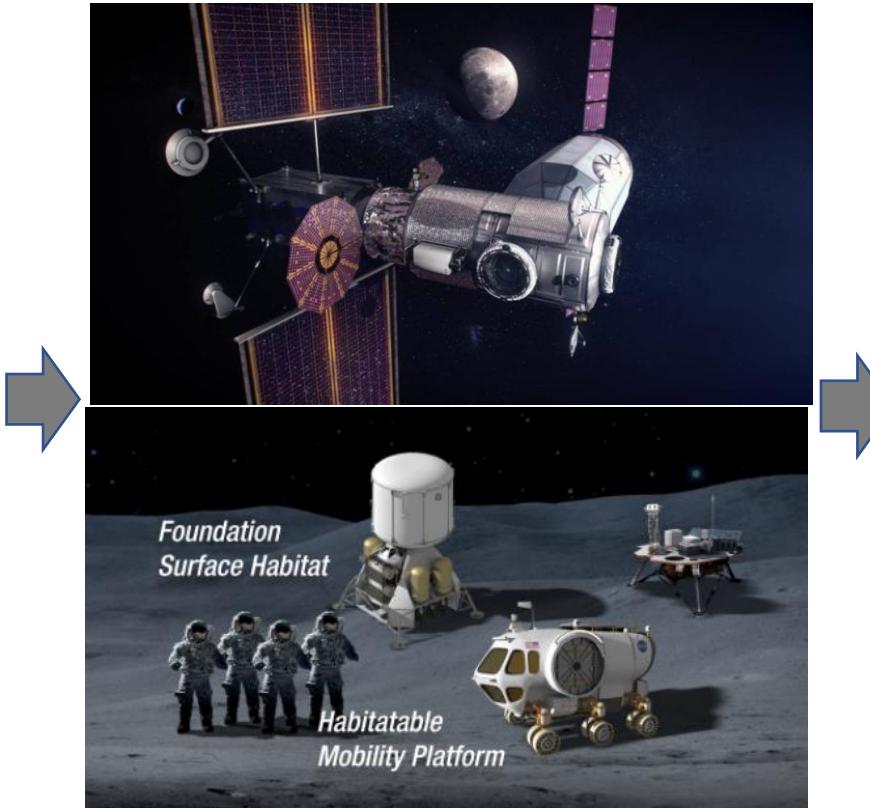
Printing (top) and testing (bottom) of a compression cylinder with a regolith simulant/polymer feedstock.

The Vision of Space Sustainability

Manufacturing in space is a destination-agnostic capability and has clear mission benefits beyond low earth orbit, where cargo resupply opportunities become more limited. These technologies are key enablers for sustainable space exploration.



ISS is the testbed for ISM.



ISM capabilities demonstrated on ISS are applicable to Gateway and the lunar surface.



"Houston, we have a solution."



www.nasa.gov/spacetech

BACK-UP

Consumables and Feedstock Production: *Living off the Land*

Products

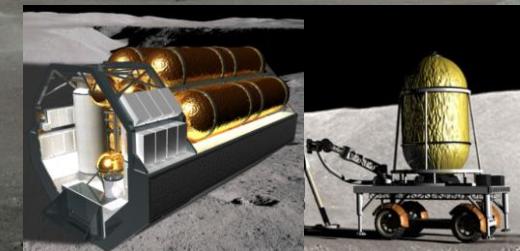
- Oxygen
- Water and other volatiles
- Consumables for in-space and surface transportation and crop growth
- Feedstock materials for manufacturing, e.g. metals and silicates
- Feedstock constituent materials for construction
- Production of commodities for future lunar economy



Excavation & Regolith Processing for O₂ & Metal Production



Consumable Storage & Delivery



Consumable Users

Rovers & EVA Suits



Habits & Life Support



Landers



NASA Lunar Surface Innovation Initiative (LSII)

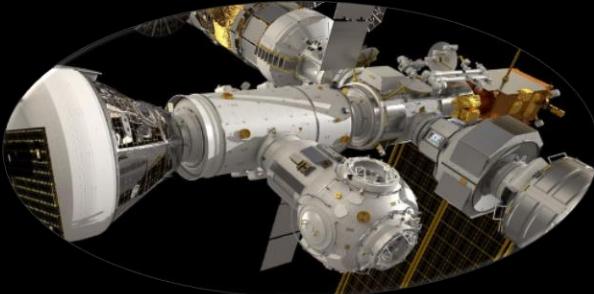




EXPLORE – ADVANCED MANUFACTURING: Develop technologies supporting emerging space industries including In Space/Surface Manufacturing

Across the Space Technology portfolio spanning the range of technology readiness levels and supporting many other Primary Capabilities

LIGHTWEIGHT COMPOSITES SPACECRAFT



- > 30% More Payload, Equipment and Experiments

UNITED STATES MANUFACTURING PUBLIC/PRIVATE PARTNERSHIPS



- Manufacturing technology has a multiplier effect to competitiveness and expands the industrial base

IN-SPACE SPARES AND REPAIRS



- > 50% mass reduction, > 99% 3D printer readiness with sustainable supply chain, multiple materials

3D PRINTING AFFORDABLE ROCKET ENGINES



- > 30% Cost reduction, three months instead of five years, Parts >1,100 to <10

INDUSTRIES OF THE FUTURE POWERED BY DIGITAL TWINS AND ARTIFICIAL INTELLIGENCE



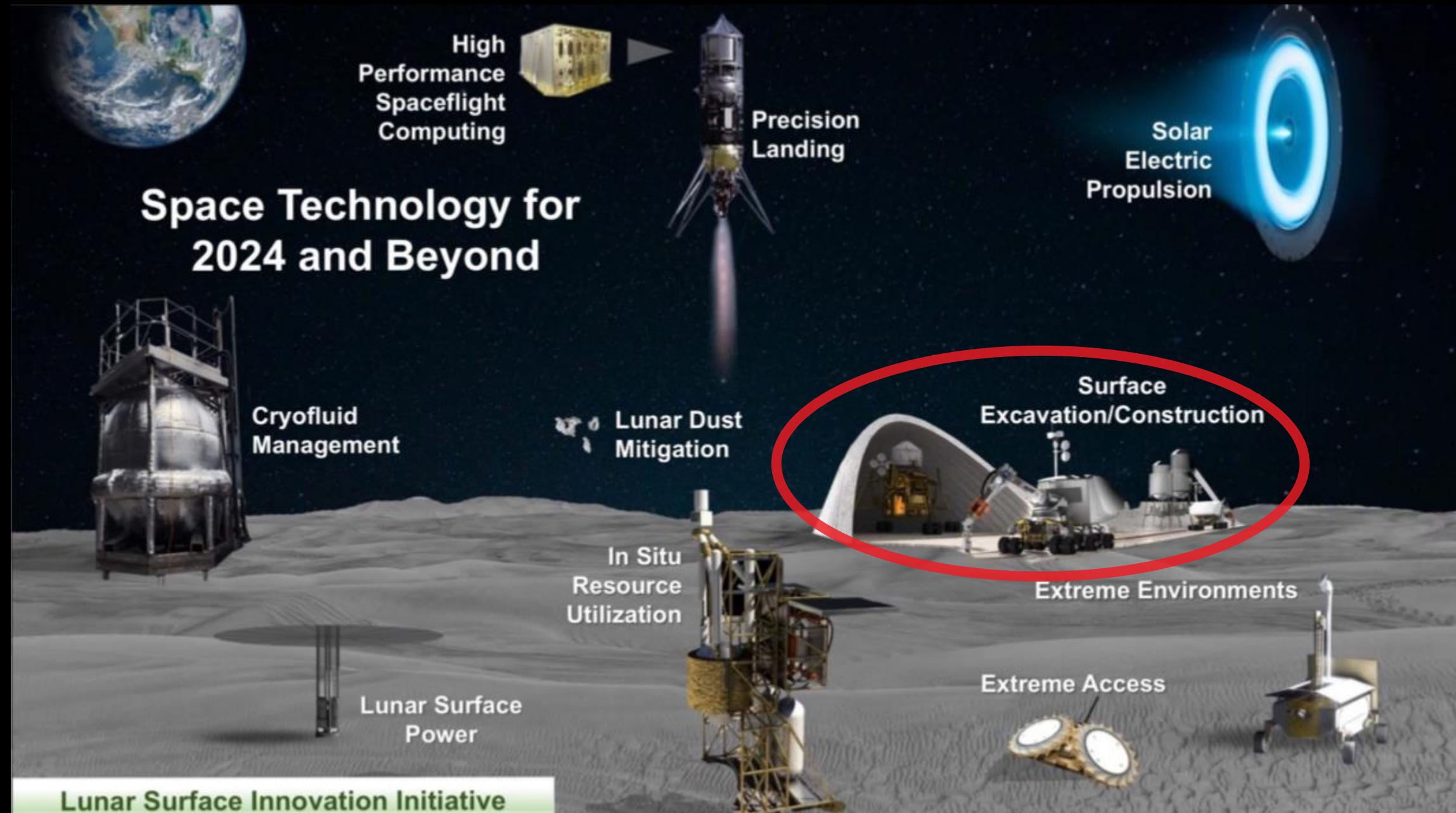
- More intelligent and more accurate predictions and capabilities, > 50% of physical resources replaced with virtual

FACTORIES IN SPACE AND SPACE INFRASTRUCTURE



- Creating economic opportunities - increased launches, spacecraft, products

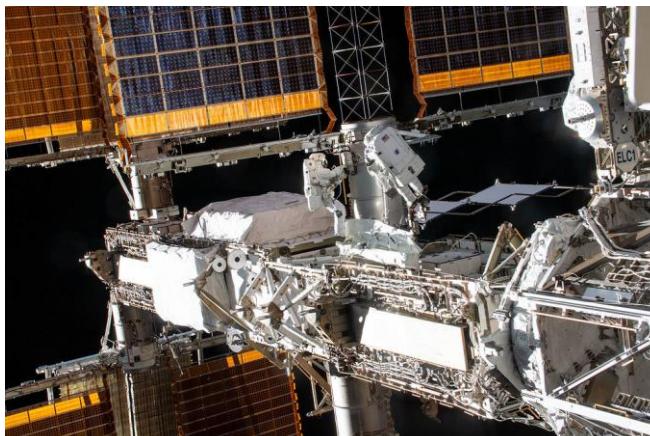
NASA Lunar Surface Innovation Initiative (LSII)



In Space Manufacturing Project Portfolio

In-Space Manufacturing (ISM) Project Portfolio:

- On-Demand Manufacturing of Metals (ODMM), Technical Lead: Dr. Christopher Roberts
- On-Demand Manufacturing of Electronics (ODME), Technical Lead: Curtis Hill
- Recycling and Reuse of materials (RnR), Technical Lead: Alex Blanchard.



ISS - Demonstrate

https://www.nasa.gov/mission_pages/station/images/index.html



Gateway – Use (Small Scale)

<https://www.nasa.gov/gateway/images>



Habitat – Use (Large Scale)

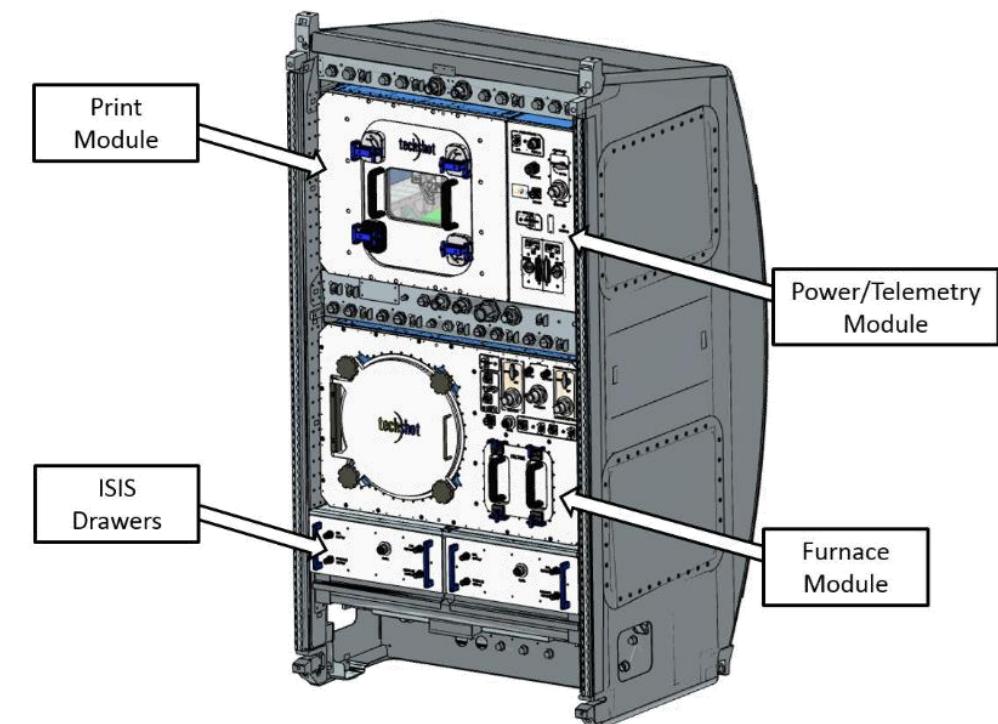
https://www.nasa.gov/centers_marshall/news/releases/2020/nasa-looks-to-advance-3d-printing-construction-systems-for-the-moon.html
Credits: ICON/SEArch+

Techshot Fabrication Laboratory (FabLab):

Goal: The Techshot FabLab aims at maturing a bound metal deposition system capable of producing Ti64 components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.

Background:

- Bound metal deposition technology
 - A paste or filament is used to print a “green” part
 - Astronaut transfers “green” part to furnace chamber.
Furnace combines a low temp thermal debind to remove binder and a high temperature sinter procedure to consolidate material
 - Finishing milling completes high precision features
- Started under AES with a NextSTEP BAA
 - Result: ground-based prototype manufacturing facility that printed, debound, and sintered Ti64 parts from a paste feedstock.



In Space Manufacturing: ODMM

Vulcan from Redwire:

Goal: The Vulcan System aims at maturing a Wire+Arc Additive Manufacturing (WAAM) system capable of producing aluminum components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.



Vulcan prototype system. Image credit: Redwire

Background:

- WAAM Technology
 - Creates near-net-shape part using a MIG type process
 - Final geometry machined from the primitive.
 - Reduced argon flow minimizes consumables
- Started under the SBIR project and completed a Phase I, II, and II-E.
 - Result: ground-based prototype of critical systems and demonstration of manufacturing using Al4043 welding wire.

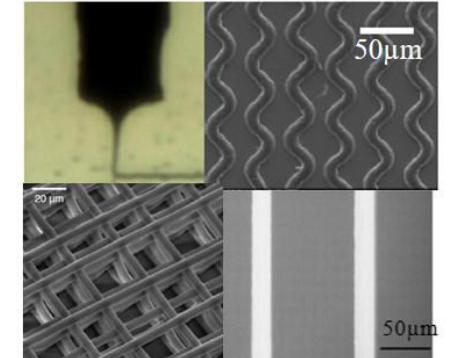


EDU Vacuum Chamber. Image credit: Redwire

In Space Manufacturing: ODME

Development of Thin Film Deposition Capability in Microgravity

- Objective: Evaluate alternate thin film deposition systems for use in microgravity.
- Threshold: 300 microns resolution (minimum printable feature size)
- Goal: 100 micron or better resolution.
- Current State-of-the-Art (SOA) of printed resolution of electronic materials is between 30 and 50 microns for analogous ground-based processes.



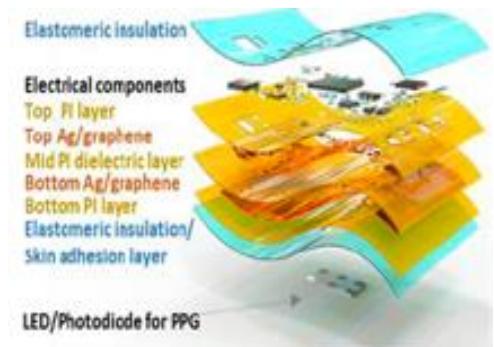
Development of Multilayer Technology for Microgravity

- Objective: Develop materials, processes, and hardware necessary for the stacking of circuitry layers of printed electronics.
- Threshold: fabricate single layer printed “board” in microgravity
- Goal: fabricate multi-layered electronic devices in microgravity

Electrohydrodynamic inkjet deposition for microgravity

Development of Validation and Verification In-Situ Capability for Flight Demo

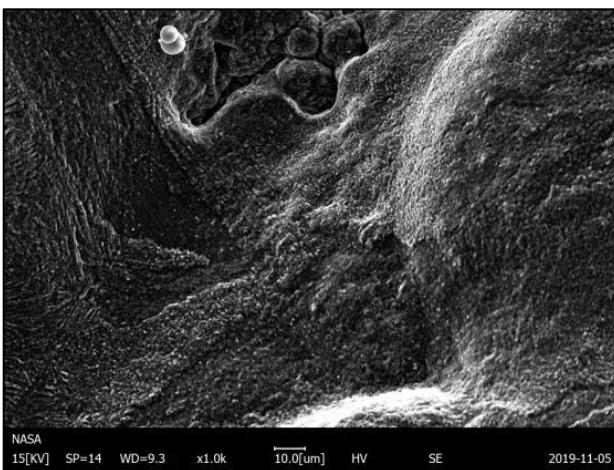
- Objective: Develop test procedures, software, and hardware to test function and operation of the ODME printed flight demo on ISS.
- Two-year project to develop and evaluate optimum methods, hardware, and integration to the 3D printer operation, in order to effectively validate the operation of flexible hybrid electronics sensors and devices.



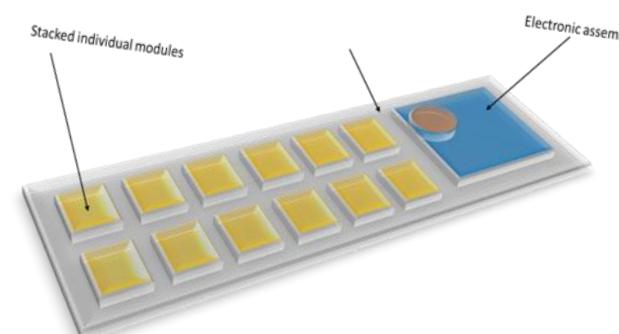
Multilayer thin film printed device

Sensor & process/materials development development at MSFC

- Development of post-processing processes.
 - Evaluating laser sintering, photonic sintering, and UV curing.
- Development of materials and processes for printing of electronics and sensors
- Testing and verification of sensors, printed devices from collaboration partners.
- Materials development and printing support to our various collaboration partners.
- Leading center for the development of printed power generation and energy storage technologies.
- MSFC ODME provides the planning and project direction for other NASA ODME groups and collaboration partners



Laser sintered Ti64



Flexible, printed thermoelectric
for power generation



nScrypt Multimaterial 3D printer

Sensor development at Ames Research Center

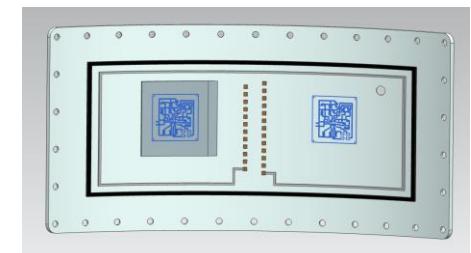
- Two groups at ARC working ODME project:
 - Biosensor development for printed cortisol and other wearable biosensors
 - The other group develops the technology for environmental sensors as well as supporting the development of energy and power applications.



Printed cortisol sensor

ODME development at Goddard Space Flight Center

- GSFC ODME group is leading the Sounding Rocket test flight development effort
- Their ODME and Power groups are evaluating flexible batteries for the wearable sensor devices



Sounding Rocket test flight

In Space Manufacturing: RnR

Goal: Develop and demonstrate recyclable packaging materials and recycling technology in a microgravity environment.

Why? The current logistics model is unsustainable for long duration space missions. Recycling and reuse has the potential to reduce mass, increase mission flexibility, provide a path towards sustainable on demand manufacturing.

Technology Product Capability

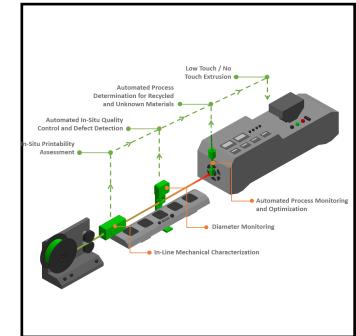
- Developing and demonstrating recycling and in-situ resource manufacturing technologies for NASA Exploration Missions. This includes testing & advancing the desired technologies, as well as establishing the required skills & processes for the processes that will enable the technologies to become institutionalized.

Technical Capabilities

- Development of Recyclable Packaging Materials and Processes
- Development of In-Process Monitoring technologies for filament feedstock production
- Demonstration of regolith/polymer blend printing on orbit
- Demonstration of a closed-loop recycling ecosystem of flexible thermoplastic polyurethane material



Recyclable Packaging Materials
Image Courtesy of Cornerstone Research Group



In Process Monitoring Suite Image
Courtesy of Cornerstone Research Group



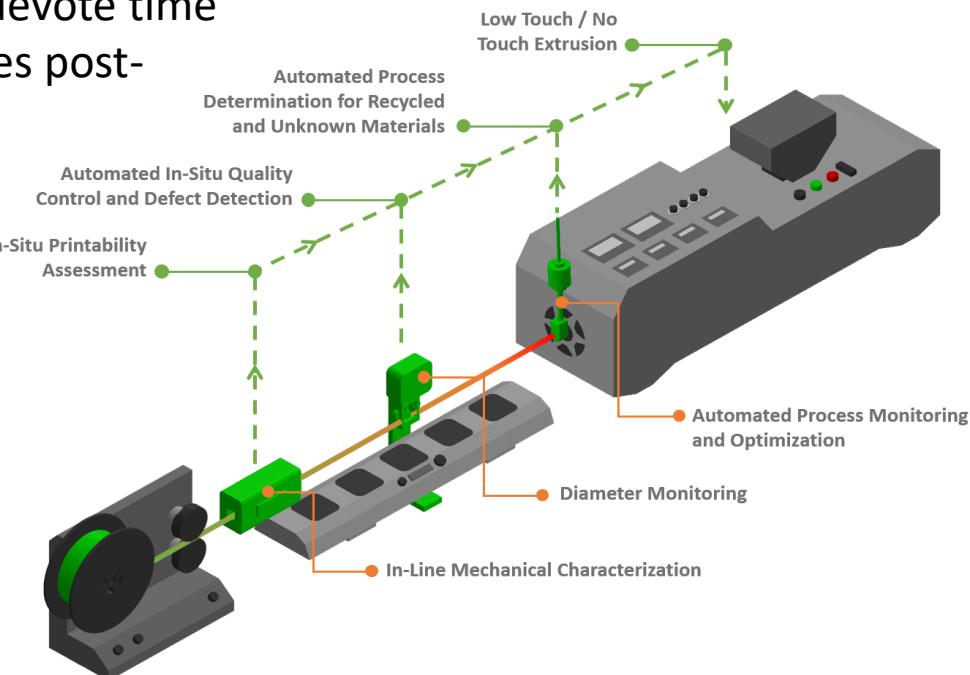
Regolith Polymer Printing Image
Courtesy of Redwire

Goal: Develop a suite of tools that can feed data back to control an extruder leading to filament production with a consistent diameter within a tight threshold.

Why: Astronauts challenged with critical mission success will be unable to devote time to ensure high-quality filament. Additionally, inconsistent filament properties post-recycling can lead to poor filament diameter control.

In Process Monitoring

- Wound down a two-year effort with Cornerstone Research Group (CRG) to develop an in-process monitoring system for polymer filament production. (Completed August 2021)
- Demonstrated successful closed loop feedback control of the polymer extrusion process.
- Integrated diameter measurement capabilities with extrusion controller.
- Accurate and precise measurements of filament over extended periods were achieved.
- 2.5 lbs. of RVT and 0.8 lbs. of polycarbonate filament were produced.



In Process Monitoring Suite Image Courtesy of Cornerstone Research Group

Goal: Demonstrate polymer/regolith simulant blend printing on station.

Why: As people move beyond low-Earth orbit to other celestial bodies the need for in-situ resource utilization for the fabrication of habitats will be necessary.

Redwire Regolith Print (RRP):

- Developed concept of operations, systems requirements, specimen matrix for flight and ground-based printing for technology demonstration mission, assembly of new print heads and print beds for the additive manufacturing facility (AMF), and development of linear low-density polyethylene/regolith simulant blend.
- Launched 8/10/2021
- Anomalies seen on orbit.



The Redwire Regolith Print facility suite, consisting of Redwire's Additive Manufacturing Facility, and the print heads, plates and lunar regolith simulant feedstock that will be launching to the International Space Station.

Image Credit: Redwire Space, Inc



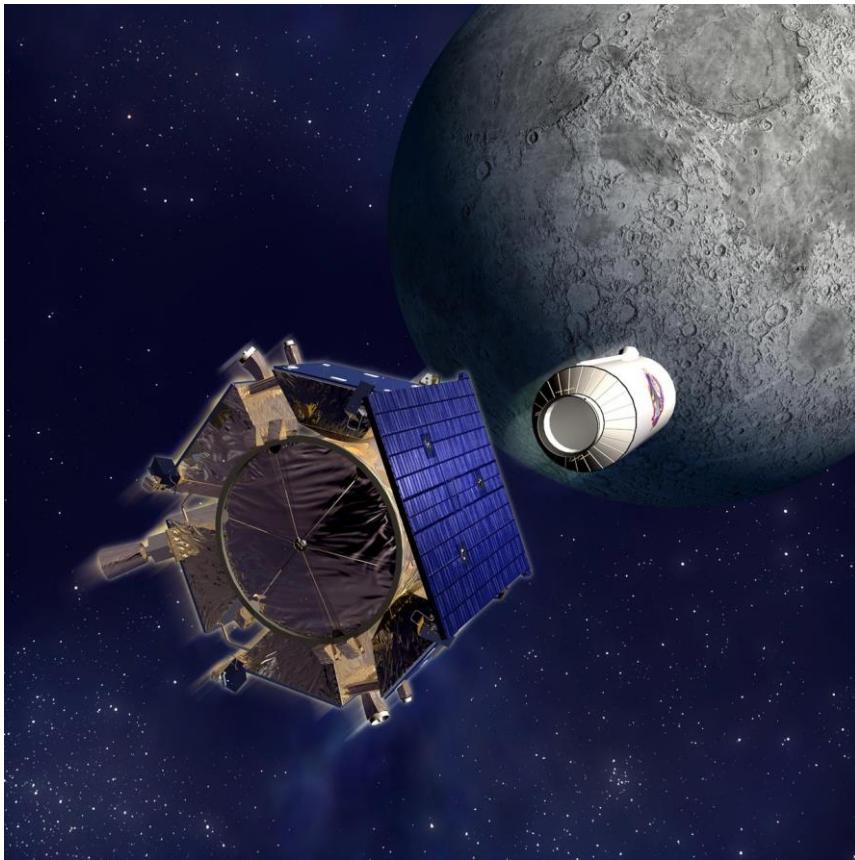
3D Printing of regolith-based feedstock material.
Image credit: Made in Space.

The technologies developed by ISM are just the beginning.

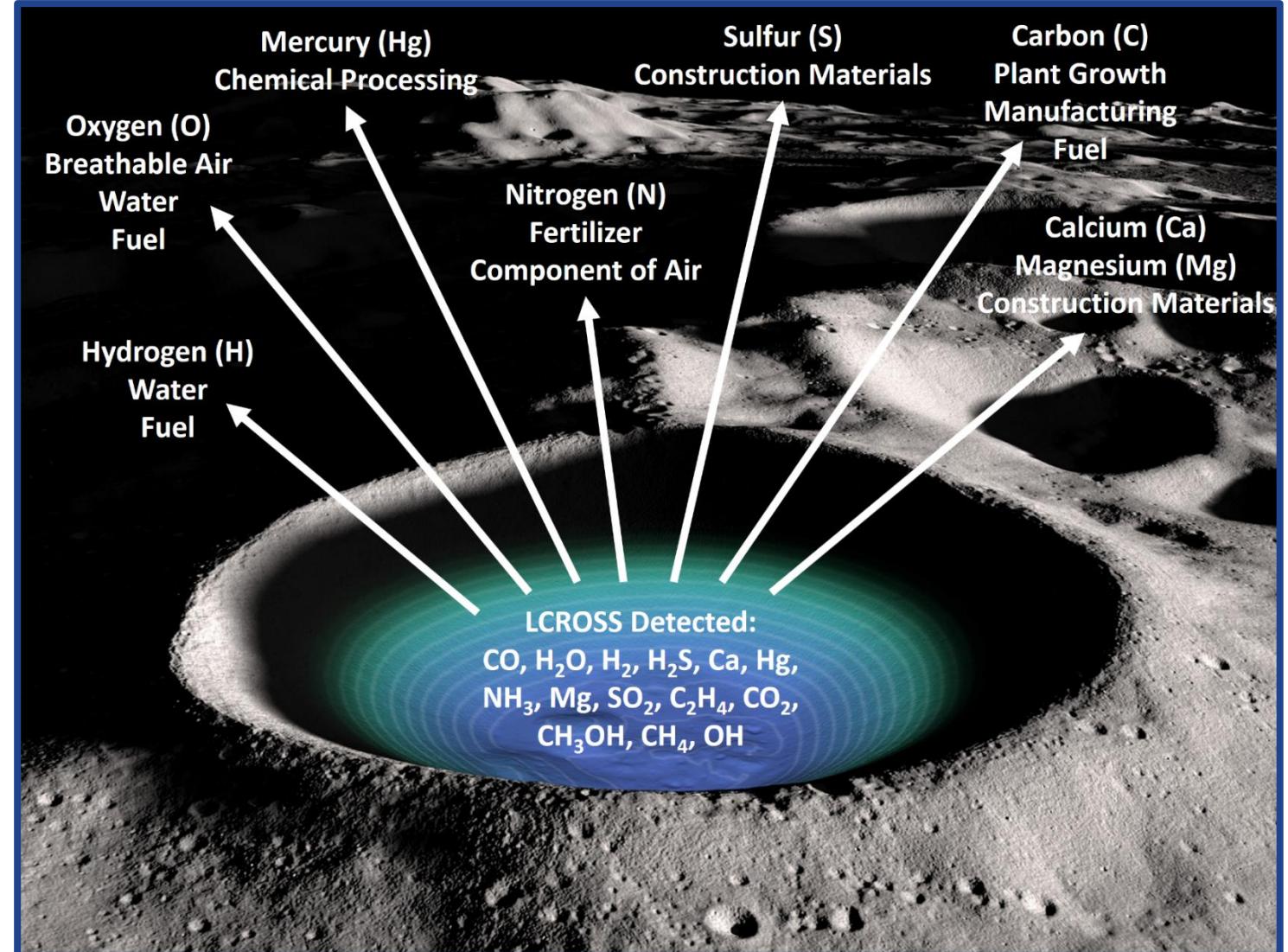
Support technologies need to be developed:

1. Geometric Inspection
2. Volumetric Inspection
3. Mechanical Characterization
4. Cleaning Procedures
5. Post Processing Techniques
6. Standards for In Space Manufacturing (or implementation of existing standards)

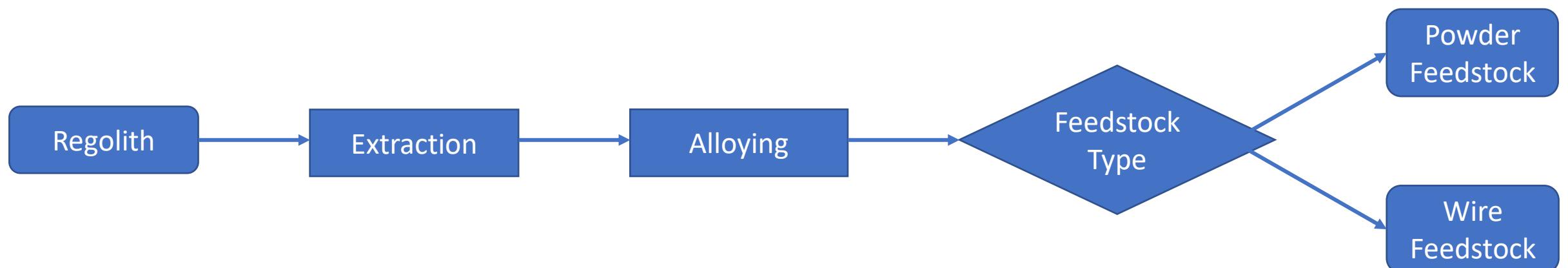
Leveraging Lunar Resources



Lunar CRater Observation and Sensing Satellite (2009)



- Extraction of elements/compounds from regolith on an industrial scale
- Conversion of extracted elements/compounds into manufacturing or construction precursors (e.g., metal alloys, cement components)
- Production of usable manufacturing or construction feedstock (e.g., creating metal microspheres for powder bed fusion, metal wire for free form fabrication, or combining cement components into cement)



Lunar regolith must be used for multiple applications (consumables, manufacturing, infrastructure construction) to enable a sustainable human presence and future lunar economy



Anorthite
 $\text{CaAl}_2\text{Si}_2\text{O}_8$



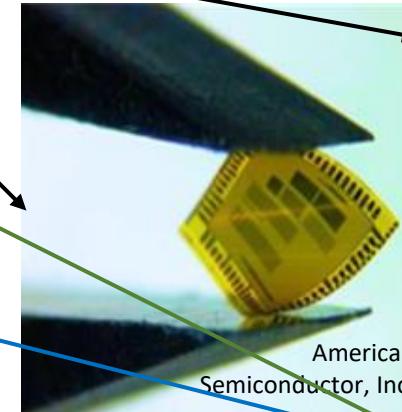
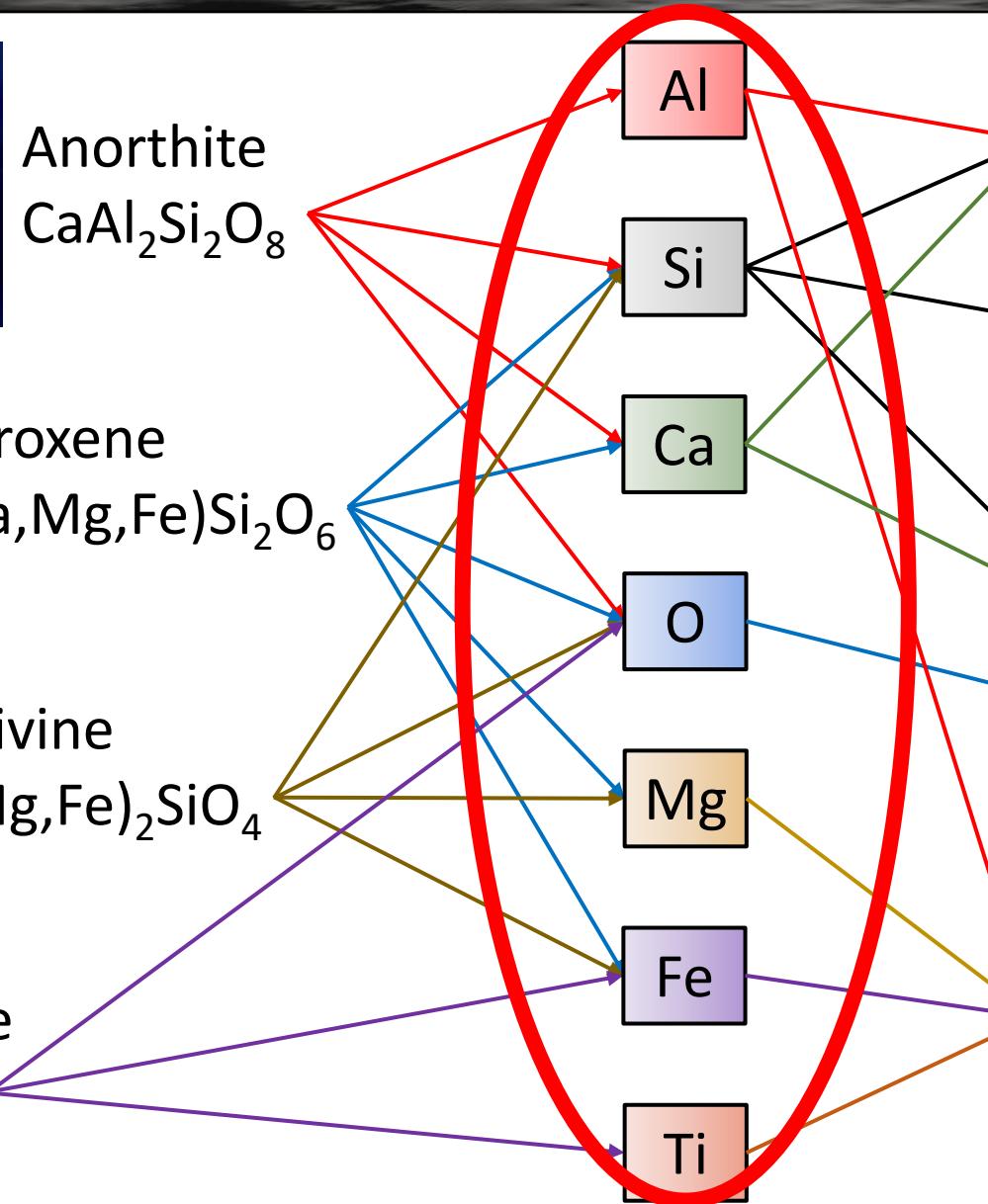
Pyroxene
 $(\text{Ca}, \text{Mg}, \text{Fe})\text{Si}_2\text{O}_6$



Olivine
 $(\text{Mg}, \text{Fe})_2\text{SiO}_4$



Ilmenite
 FeTiO_3



American Semiconductor, Inc.



Made In Space

